Contributions of lower extremity joints to energy dissipation during landings

SONG-NING ZHANG, BARRY T. BATES, and JANET S. DUFEEK

Exercise Science Unit, Biomechanics/Sports Medicine Laboratory, The University of Tennessee, Knoxville, Knoxville, TN 37996; and University of Oregon, Eugene, OR

ABSTRACT

ZHANG, S-N., B. T. BATES, and J. S. DUFEEK. Contributions of lower extremity joints to energy dissipation during landings. Med. Sci. Sports Exerc., Vol. 32, No. 4, pp. 812-819, 2000. Purpose: The purpose of the study was to investigate changes in lower extremity joint energy absorption for different landing heights and landing techniques. Methods: Nine healthy, active male subjects volunteered to perform step-off landings from three different heights (0.32 m, 2.5 m; 0.62 m, 3.5 m; and 1.03 m, 4.5 m) using three different landing techniques (soft, SFL; normal, NML; and stiff landing, STL). Each subject initially performed five NML trials at 0.62 m to serve as a baseline condition and subsequently executed five trials in each of the nine test conditions (3 heights × 3 techniques). Results: The results demonstrated general increases in peak ground reaction forces, peak joint moments, and powers with increases in landing height and stiffness. The mean eccentric work was 0.52, 0.74, and 0.87 J-kg⁻¹ by the ankle muscles, and 0.94, 1.31, and 2.15 J-kg⁻¹ by the hip extensors, at 0.32, 0.62, and 1.03 m, respectively. The average eccentric work performed by the knee extensors was 1.21, 1.63, and 2.26 J-kg⁻¹ for the same three heights. Conclusions: The knee joint extensors were consistent contributors to energy dissipation. The ankle plantarflexors contributed more in the STL landings, whereas the hip extensors were greater contributors during the SFL landings. Also a shift from ankle to hip strategy was observed as landing height increased. Key Words: STRATEGIES, MECHANICAL DEMAND, MUSCULAR WORK

During foot contact with ground in vigorous locomotion, the body experiences tremendous impact forces. Maximum vertical ground reaction force values as high as 14.4 times body weight (BW) have been reported (20) for single-leg landings from a double somersault. Stacoff et al. (25) showed that the first peak (F1) of the vertical component of ground reaction force (GRF) ranged from 1000 to 2000 Newtons (N), whereas the second peak (F2) values ranged from 1000 to 6500 N in landings after a volleyball block jump. McNitt-Gray (17) demonstrated that the maximum vertical ground reaction forces for trained gymnasts were 3.9, 6.3, and 11.0 times BW for landing from heights of 32, 72, and 128 cm, respectively. Accumulation of high impact forces may pose a threat to the integrity of the lower extremity and related overuse injuries are often direct consequences of these impacts (22,23). Many of these injuries are often associated with the knee-joint structure and reported as common in running (16), basketball (19), tennis (24), football (15), volleyball (12), skiing (10), and the triathlon (3). Fifty-eight percent of all injured female basketball players were engaged in landing from a jump at their time of injury (13) and 40% of high-level volleyball players experienced knee problems during their playing careers (11). James et al. (16) reported knee pain as the most common problem for runners.

The studies on biomechanical behaviors of the lower extremity in landing have been focused on prediction of impact forces (9), comparisons of landing techniques (4), effects of landing velocities (18), and manipulations of landing distances, heights, and techniques (8). Dufek and Bates (8) demonstrated greater peak moments of the proximal extensors (i.e., hip extensors) compared with the distal extensors (i.e., plantarflexors). Few studies, however, investigated the contributions of various lower extremity muscle groups to the total energy dissipation. DeVita and Skelly (4) suggested that the ankle joint plantar flexors absorbed more energy in a stiff landing, whereas the hip and knee extensors absorbed more energy in the soft landing. McNitt-Gray (18) demonstrated that elite gymnasts dissipated more energy with ankle and hip extensors at the higher height compared with their recreational counterparts, whereas the latter group adjusted their strategy by increasing hip flexion and by
The literature regarding the various contributions made by the lower extremity muscle groups to the reduction of impact and energy. The femur and tibia are among the longest bones in human body and significantly greater loading at the knee joint are expected. High mechanical output by the knee musculature should be experienced consequently. Research in this area, however, still fails to agree on the issue. Therefore, the purpose of the study was to investigate changes in energy absorption of lower extremity joints for different landing heights and landing techniques.

METHODS

Nine active men (ages: 25 ± 5 yr, mass: 74.4 ± 6.3 kg) volunteered to participate as subjects in the study. Each subject signed an Informed Consent Form approved by the Institutional Review Board at the University of Oregon, which was consistent with the human subject policy of the American College of Sports Medicine before the experimental sessions. All subjects were actively involved in recreational sports on a regular basis (at least 2–3 times per week) and had participated in sporting activities requiring jumping/landing skills. They were free of injury or other physical impairment in the lower extremity at the time of testing.

The subjects participated in two test sessions. The first test session was used to familiarize the subjects with the experimental protocol and to obtain mean maximum knee flexion angles for the nine test conditions that were combinations of soft (SFL), normal (NML), and stiff (STL) landing techniques (stiffness) and three landing heights (0.32 m, 0.62 m, and 1.03 m). The subjects were asked to perform five landing trials in each of the 10 conditions and the right knee flexion angles were monitored using an electrogoniometer (Penny and Giles, 1000 Hz). The mean maximum knee flexion angles obtained were used to determine the range of maximum knee flexion angle for each of the nine test conditions for each subject with the following equation:

$$\alpha_{range} = \alpha_{max} \pm 9^\circ$$

where $$\alpha_{range}$$ = range of maximum knee flexion angle and $$\alpha_{max}$$ = mean maximum knee flexion angle. The 9° criterion was derived from the data of maximum knee flexion of normal landings from a 60-cm height and two standard deviations were applied to ensure proper range of variation (5). The $$\alpha_{range}$$ values thus obtained for each subject at each height × technique combination (condition) were used to monitor landing technique during the second test session. Any trial with a maximum knee flexion angle beyond $$\alpha_{range}$$ was discarded and an additional landing was performed.

The second session began with an anthropometric measurement portion and was followed by the activity testing protocol. All subjects were encouraged to actively warm up before the testing. Subjects performed five step-off landing trials from a raised platform in each of the 10 conditions for a total of 50 trials. The landings were initiated with right foot leading forward, the left foot remaining in contact with the platform, and the center of gravity as steady as possible before the step-off. The subjects were instructed to keep both hands on their buttock so that their upper limbs were parallel to the sagittal plane and clear from obstructing their hip reflective markers during landing. Among the 10 conditions, the first was a base-line condition performed at the beginning with normal landing from the median height (i.e., 0.62 m). Subsequently, the subjects were asked to perform landings in nine test conditions which were a combination of SFL, NML, and STL landing trials from the three landing heights of 0.32, 0.62, and 1.03 m representing three contact velocities (i.e., 2.5, 3.5, and 4.5 m s⁻¹). The order of heights was from the lowest to the highest to minimize potential risk of injury. The landing techniques were randomized in such a way that the soft and stiff landing occurred randomly either before or after normal landing at each height.

The right sagittal view was recorded using two high-speed video cameras (200 Hz, Motion Analysis Corporation, Santa Rosa, CA) with one camera focusing on the performance of lower extremity and the other camera on the total body. The lower extremity view was mapped onto the total body view to obtain more accurate measurement of lower extremity kinematics. Retro-reflective markers were placed on the right side of the ear canal, acromion, lateral humeral epicondyle, radial styloid process, greater trochanter, lateral femoral epicondyle, lateral malleolus, heel, and head of the fifth metatarsal. Two force platforms (AMTI) were used to collect data of ground reaction forces (GRF) and moments of force for left and right limbs. Only the right side signals were used for further analyses. The electrogoniometer was placed on the right knee joint to monitor the maximum knee flexion angles and landing stiffness (technique—defined as maximum knee flexion angle) during the test sessions. The force platform and electrogoniometer signals were sampled at 1000 Hz using a biomechanical system (Ariel Dynamics Inc., Trabuco Canyon, CA). The synchronization between the video, force platform, and electrogoniometer systems was accomplished through a light-emitting-diode which was present in the video views, triggered by the force platform and fed as an analog channel to the Ariel system. The video images were digitized to obtain coordinates of the joints using the commercial software (Motion Analysis). The data of the kinematic coordinates, ground reaction forces, and moments were imported into customized software to compute typical joint kinematics, segmental inertia properties (14), and joint kinetics via an inverse dynamics model (26).

The variables evaluated included the range of motion (ROM) of the three lower extremity joints, peak GRF, peak joint moments and powers, and total eccentric work performed by the different lower extremity muscle groups. Critical values were assessed with statistical procedures, and the time-history of the kinematic and kinetic variables was examined qualitatively. The ground reaction forces and joint kinetic values were normalized to the body mass for each individual subject while the representative moment and power curves were normalized to landing phase; the latter was defined as the time from foot contact to the minimal

LANDING BIOMECHANICS
vertical center of gravity (COG) position during landing. By convention, both the positive and negative values for joint moment would represent extensor and flexor moment, and the positive and negative power values would indicate energy generation and absorption. A three-factor $3 \times 3 \times 3$ (height $\times$ technique $\times$ joint) univariate analysis of variance (ANOVA) was computed for the total work performed by lower extremity muscle groups. Two-factor $3 \times 3$ ANOVAs (height $\times$ technique) were performed on the peak GRF, ROM, and moment and power variables. Because the peak moments and powers do not occur at the same time and do not fully reflect the total effort involved in the energy reduction, only the height and technique were adopted as the factors without consideration of the joint in the analyses. Unless mentioned otherwise, the significant level for difference was set at $P < 0.05$.

**RESULTS**

Ground reaction force magnitudes. The typical time-history curve of the vertical ground reaction force demonstrated two distinctive maximums with first peak (F1) related to toe contact and second peak (F2) associated with heel contact (6.7). A summary of the selected critical events collapsed by height across techniques and by technique across heights is provided in Table 1. The $3 \times 3$ ANOVA (height $\times$ technique) results for F1 and F2 demonstrated significant omnibus $F (P < 0.0001)$, significant main effects for height and technique ($P < 0.0001$), and insignificant height $\times$ technique interactions ($P > 0.05$). Due to the lack of interactions, the data were collapsed across three techniques for each height and across three heights for each technique (Table 1). Similar combinations were also made and presented for the ROM, peak moment, and power variables. The peak GRF values (F1 and F2) increased significantly ($P < 0.05$) from the lower to higher heights. When comparing these values under the increased landing stiffness conditions, the significantly augmented peaks were observed as well (Table 1). These results demonstrated a trend of the increased loading to the body with increases in either landing height or landing stiffness.

Joint ROM. A change of landing technique (stiffness) is practically defined as a change of lower extremity joint angles during landings. More specifically stiffness was defined as a change of maximal knee joint flexion angle during the landing phase in this study. The $3 \times 3$ ANOVA (height $\times$ technique) results indicated highly significant omnibus $F (P < 0.0001)$, and significant main effects for height and technique ($P < 0.0001$) for the hip, knee, and ankle ROM. The hip and ankle ROM demonstrated insignificant interactions between height and technique, whereas the interaction for the knee ROM was significant ($P < 0.01$). The collapsed mean ROM values for the lower extremity joints generally increased with enhancements in landing height except the changes in the ankle ROM from 62 to 103 cm (Table 1). Meanwhile the decreases in the ROM with increases in landing stiffness (technique) were seen across all three joints except the changes in the ankle joint ROM from SFL to NML. The ankle joint ROM maintained small changes from SFL to STL and the most drops in ROM at all three heights were accounted for mainly by the hip and knee joint.

Kinetics. Mean representative curves of hip, knee, and ankle joint moment and power normalized to landing phase for NML at 0.62 m are provided in Figure 1 and 2. Two distinctive peaks of first (AM1 and KM1) and second (AM2 and KM2) maximum moment were present in both ankle and knee joint moment curves (Fig. 1). Only one significant peak was observed in hip joint moment (HM) during the impact phase of landing. Similarly, two minimums were observed for the power curves for the ankle (AP1 and AP2), and knee (KP1 and KP2) joint, whereas only one minimum was observed from the hip (HP) joint (Fig. 2). The maximum and minimum values in the moment and power curves occurred approximately at T1 and T2, indicating their close associations with the first and second impact forces.

Peak extensor moments and powers represent maximum efforts by certain muscle groups in energy absorption. The

<table>
<thead>
<tr>
<th>Condition</th>
<th>F1 (N·kg⁻¹)</th>
<th>F2 (N·kg⁻¹)</th>
<th>Ankle ROM (°)</th>
<th>Knee ROM (°)</th>
<th>Hip ROM (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>8.27*</td>
<td>25.14*</td>
<td>30.24*</td>
<td>52.02*</td>
<td>40.22*</td>
</tr>
<tr>
<td></td>
<td>(2.58)</td>
<td>(8.52)</td>
<td>(7.44)</td>
<td>(21.02)</td>
<td>(26.75)</td>
</tr>
<tr>
<td>62</td>
<td>17.30*</td>
<td>32.17*</td>
<td>32.99</td>
<td>56.74*</td>
<td>49.86*</td>
</tr>
<tr>
<td></td>
<td>(4.55)</td>
<td>(8.27)</td>
<td>(6.82)</td>
<td>(19.11)</td>
<td>(26.94)</td>
</tr>
<tr>
<td>103</td>
<td>30.60*</td>
<td>46.59*</td>
<td>34.42*</td>
<td>63.61*</td>
<td>65.35*</td>
</tr>
<tr>
<td></td>
<td>(6.07)</td>
<td>(10.24)</td>
<td>(7.74)</td>
<td>(17.42)</td>
<td>(24.25)</td>
</tr>
<tr>
<td>SFL</td>
<td>16.49*</td>
<td>29.17*</td>
<td>34.38</td>
<td>77.04*</td>
<td>79.28*</td>
</tr>
<tr>
<td></td>
<td>(9.48)</td>
<td>(11.14)</td>
<td>(7.58)</td>
<td>(10.65)</td>
<td>(19.35)</td>
</tr>
<tr>
<td>NML</td>
<td>18.41*</td>
<td>32.97*</td>
<td>34.58*</td>
<td>58.72*</td>
<td>50.78*</td>
</tr>
<tr>
<td></td>
<td>(10.48)</td>
<td>(11.39)</td>
<td>(6.72)</td>
<td>(9.92)</td>
<td>(16.46)</td>
</tr>
<tr>
<td>STL</td>
<td>21.08*</td>
<td>41.45*</td>
<td>28.69</td>
<td>36.87*</td>
<td>25.37*</td>
</tr>
<tr>
<td></td>
<td>(10.34)</td>
<td>(11.06)</td>
<td>(6.75)</td>
<td>(11.97)</td>
<td>(15.57)</td>
</tr>
</tbody>
</table>

Values in parenthesis are standard deviation (SD); Significant difference level; $p < 0.05$; see text for full description of the variables.
$3 \times 3$ ANOVAs (height \times technique) were performed for these variables. Significant effects were noticed for the omnibus $F (P < 0.0001)$, the main effects ($P < 0.0001$), and insignificant interactions between height and technique (except KM2). The values of AM1 and AP1 were significantly lower than the values of AM2 and AP2 for all conditions, indicating minimum effect of ankle plantarflexors in the impact absorption at T1 (Tables 2 and 3). However, the knee extensors became increasingly involved in the absorption of the first impact force at the two higher heights. The peak hip moment and power that occurred later than AM1 and KM1 demonstrated significantly greater values than that of peak ankle and knee extensor moments and power (Table 2 and 3). The timings for those peaks were consistent and arranged in a sequential manner (Figs. 1 and 2).

The mean absolute and relative eccentric work is provided in Table 4. A $3 \times 3 \times 3$ ANOVA (height \times technique \times joint) was conducted on the eccentric work
performed by the lower extremity. The result demonstrated significant omnibus F, significant main effects for height, technique and joint, and significant two-way interactions for joint × height and joint × technique (P < 0.01). The interaction between height and technique was not significant (P > 0.05) and no significant three-way interactions were found. Two 3 × 3 ANOVAs (joint × height and joint × technique) were conducted as follow-up analyses. The interactions between joint and height as well as joint and technique are shown in Figure 3. The absolute mean values of eccentric work during the landing phase displayed the trends of change that are slightly different from the relative (percent) eccentric work (Table 4). For absolute work, the ankle muscle group predominantly demonstrated increased work with the increases in landing heights and slight improvement of eccentric work from SFL to STL. The hip and knee joint extensor groups showed general decreased eccentric efforts with increased stiffness and improved work values with increased landing heights (Table 4, Fig. 3). For the relative eccentric work, however, the knee joint maintained consistent and high mechanical outputs in all landing conditions. Meanwhile, the ankle muscles demonstrated increased contributions (12.5% to 38.1%) and the hip extensors showed decreased contributions (45.3% to 20.9%) to the total energy dissipation as the landing stiffness increased. The increases in landing heights did not influence the relative contributions of each of the three lower extremity muscle groups consistently (Table 4). Clear anticipation by the subjects was demonstrated by the joint positions at contact; these data suggested that the initial ankle joint positions remained constant while the initial knee and hip joint angles demonstrated overall decreases as the landings became stiffer.

**DISCUSSION**

The purpose of the study was to examine changes in lower extremity joint energy absorption for different landing heights and landing techniques. The changes in the landing heights and the landing techniques are closely related to the changes in mechanical demands placed on human body during the landing activities. The effects of mechanical demands placed on the lower extremity and the corresponding mechanical responses of lower extremity musculature during landing can be examined by evaluating changes in landing techniques in relation to landing heights and the
interaction of these two factors. The results suggest that there are general increases in biomechanical responses with increased landing heights. However, the two peak ground reaction forces responded differently with such changes. The average and relative increases with respect to the lowest height (0.32 m) were 136% for F1 and 44% for F2 with all three landing techniques, indicating a more Newtonian/mechanical response from the subjects for F1 than for F2 without much neuromuscular intervention. The average times from the contact to F1 and F2 were 9.6 and 4.2 ms. The F2 responses occurred much later after the first impact and therefore were considered more neuromuscular, allowing more time for the lower extremity muscles to absorb the impact. DeVita and Skelly (4) observed a pre-contact muscular activity during landing, which suggests a preset central neuromuscular program. This anticipation may enhance the tension of the musculotendinous structures in the foot and ankle, and other lower extremity regions before the occurrence of landing contact so that greater energy dissipation may happen immediately after the impact.

As mentioned previously, the mechanical demands increased with an increase in landing heights. All three lower extremity extensor groups responded with an increase in peak and total mechanical output for the same technique (Tables 2–4). However, these changes were not undertaken in similar fashion among the different lower extremity muscle groups. Although the eccentric work performed by the ankle plantarflexors was increased slightly, the increases in the work done by the knee and hip extensors was more apparent as the height changed from 0.32 to 1.03 m (Table 4). The absolute work data from this study suggested that the ankle muscle group was less capable of energy absorption compared with hip and knee muscle groups, especially at the two higher heights. The proximal muscles of the lower extremity tend to be larger in volume than the distal muscles; this is mainly due to greater cross-sectional areas (27), longer muscle fibers, and relatively shorter tendons (1). This arrangement reduces the moment of inertia relative to the hip joint and allows the leg to move more efficiently while it also limits the capacity of energy absorption and generation in more distal muscle groups. It has been suggested by several investigators that biarticular muscles are used for power transportation during locomotion (21). Prilutsky and Zatsiorsky (21) demonstrated that the direction of

![Figure 3](image-url)
power transfer during landing was from distal to proximal segments; it is therefore logical to assume that the energy generated before landing contact can be transported from the distal end to the more proximal and massive muscle group for further dissipation during impact. An indirect evidence from this study indicated that the peak powers reached at different times with the second peak knee power and the peak hip power occurring at a later time than the second peak ankle power (Fig. 2).

The subjects displayed distinct strategies at the different landing heights. In other words, each joint and muscle group played significantly different roles of energy reduction in the various mechanical loading situations (Fig. 2). It was noted that the ankle maintained a stable mechanical output, whereas the eccentric work by the knee and hip joint extensors was reduced with changes of technique from the soft to stiffer landings at each height. As a result of these changes, the total work was decreased significantly due to the reduced time for energy reduction in normal and stiff landing. The knee and hip extensors were equally important in the landings with more lower extremity flexion (Table 4). As the landing became stiffer, their ability in energy reduction decreased in different fashions. The hip extensors were less effective than the knee muscles in the STL condition at the low height. The same muscle group became more involved in the energy reduction at 0.62 m and 1.03 m due to the increases in their mechanical advantages in STL with greater hip joint flexion.

The present study presented a different energy dissipation pattern than has been previously reported in the literature. The eccentric work by knee and ankle muscles was greater for the soft landings compared with the stiff landings in a study reported by DeVita and Skelly (4). In the current experiment, significant increases in knee and hip work and decreases in ankle work were observed in the soft landing condition. McNitt-Gray (18) reported high hip and knee work, and small ankle work for landings from medium and high heights (0.72 and 1.28 m) for recreational athletes using a normal landing technique. Although we observed similar changes in the knee and hip work, we saw an increase in the ankle eccentric work as the landing height increased. It is logical to argue that with the increased lower extremity flexion and longer landing phase at higher heights, the ankle musculature should perform more work. One possible explanation for the discrepancies may lay in the different activities involved in the present and previous studies. DeVita and Skelly investigated soft and stiff landings from a 0.59 m height, whereas McNitt-Gray studied the self-selected landings from three different heights. It is possible that minor changes in techniques may influence the biomechanical responses. It should be also noted that the subjects involved in this study were regular and active university students, whereas in McNitt-Gray's study, elite and recreational gymnasts were used as the subjects. It was demonstrated that the strategies were different between the two different subject groups (18). In the present research the three self-selected landing strategies were systematically manipulated at three different heights. This is the first time that all three possible techniques from three heights were systematically studied and both joint kinematic and kinetic measurements were presented. In our study, it was clearly demonstrated that the shift of energy absorption was from distal to proximal muscle groups with increased mechanical demand (i.e. increases in landing height). At the lower height, ankle and knee muscle groups were more effective in energy dissipation in the stiff landing, whereas the knee and hip extensors were more involved in the soft landing. As the height and mechanical loading increased, the lower extremity posture became more flexed and the hip extensors became increasingly involved in energy dissipation. A second possible explanation may come from the differences in the control of techniques in the studies. In the present study, the three landing techniques were self-selected and predefined in a pretest session using an electrogoniometer for each subject in each test condition. The range of maximum knee flexion using the formula shown earlier was used to monitor a subject's landing technique during the subsequent test session. Because the joint range of motion for each technique was different for each subject, this control process preserved the natural techniques of each subject under the various test conditions. Even though there is no documented evidence that a change in natural technique will lead to changes in joint kinetics during landing, it is logical to assume that such changes may occur. More research is warranted for this aspect of landing biomechanics.

Main finding in this study was revealed by examining the relative contribution of each muscle group to the total energy reduction. Although the absolute eccentric work data for the knee and hip joints suggested the increases in the energy absorption with the decreased landing stiffness at the all three different heights (Table 4), the relative work values indicated the high and consistent outputs from the knee extensors. The ankle work was increasingly important in the stiff landing at the lower heights; however, these percentages decreased with an increase in landing heights and mechanical demands. This is comprehensible due to the fact that the ankle plantarflexors exhibit lesser capacity for energy absorption (1). The hip extensors were involved minimally in STL at the low height and they became more involved as the mechanical demand increased and the hip joint posture became more flexed, due to the massive potential of energy reduction for the muscle group. These observations were supported by the facts that the relative contribution of each joint ROM to the total change of ROM demonstrated rather similar fashions (Table 1).

Landings involved in many sport activities are repetitive and violent in nature. This type of stress has long been associated with overuse injuries (22,23). With increased mechanical demands, loading to lower extremity joints escalates accordingly. It was demonstrated in this study that the knee joint consistently experienced enormous mechanical demands and high mechanical output in the different landing conditions. At the greater mechanical demands, most of energy is absorbed by the massive knee and hip extensors. Therefore, the eccentric strength and proper
REFERENCES


This study was partially supported by the Orthopedic and Fracture Clinic, Eugene, Oregon. The authors are grateful for the constructive comments and recommendations from two anonymous reviewers.

Address for correspondence: Song-Ning Zhang, Department of Exercise Science and Sport Management, Biomechanics/Sports Medicine Laboratory, The University of Tennessee, Knoxville, 1914 Andy Holt Ave., Knoxville, TN 37996; E-mail: szhang@utk.edu.